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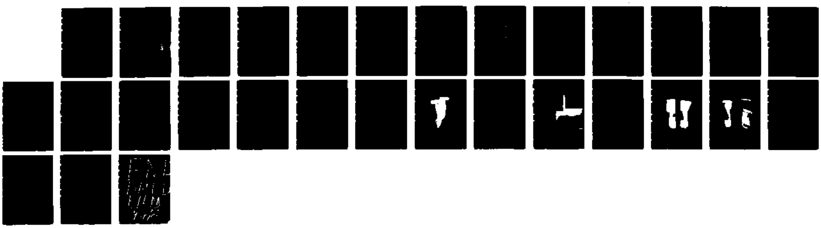

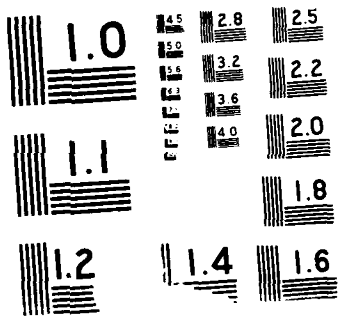
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Allied-Signal Aerospace Company
Garrett Engine Division
Phoenix, AZ 85010
Contract F33657-83-C-2004

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21-6519 January 15, 1988

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REPORT NO. 21-6519

TOTAL PAGES 24

ATTACHMENTS:

REV	BY	APPROVED	DATE	PAGES AND/OR PARAGRAPHS AFFECTED
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JTDE I
MATERIALS R&D REPORT

1.0 INTRODUCTION

This report, submitted by the Garrett Engine Division (GED), formerly the Garrett Turbine Engine Company, describes the materials research and development efforts conducted in support of the Joint Technology Demonstrator Engine (JTDE) Flowpath Test and Assessment (FTA) Program. The report is submitted in compliance with the requirements of Contract F33657-83-C-2004, CDRL item AOOF, under Data Item Description DI-S-3597.

This report details government-funded materials development for the JTDE XTE34 conducted during the period from April 1983 to August 1987.

The XTE34 was based on the ATEGG XTC34 core (Contract F33657-82-C-0194, Reference 1) with low-spool components derived from U.S. Navy programs. The Navy Mixed-Flow Fan (Contract N000140-86-C-9416) had previously been rig tested and was fabricated from well characterized conventional materials (Ti 6,4). The Navy low-pressure (LP) turbine (Contract N00140-80-C-0581, Reference 2) had also been previously warm rig tested but never tested hot. This report does not discuss materials R&D conducted under these parent component or core programs except where needed for background. Except for the GED funded efforts to replace a core impeller damaged in ATEGG testing (and therefore not available for the XTE34 Build), and providing a backup LP Turbine Stator assembly, all the materials used in the XTE34 were either standard materials or were developed under the parent programs mentioned above.

2.0 HIGH-PRESSURE COMPONENTS

2.1 Impeller

The impeller run in the JTDE XTE34 was fabricated from the titanium alloy Ti 6-2-4-6. This component was originally intended to be a hollow, dual alloy impeller, which was needed to meet the design life goals for this engine. The dual alloy impeller concept used a creep resistant titanium alloy (Ti-5Al-6Sn-2Zr-1Mo + Si) for the backface and a high tensile and fatigue strength titanium alloy (Ti-6Al-2Sn-4Zr-2Mo + Si) for the hub and blades (Figure 1). In addition, internal cavities were generated during the fabrication sequence that significantly reduced the impeller weight and bore stresses. The fabrication process is described in whole in the ATEGG Materials R&D report (report No. 21-5120A; contract no. F33657-82-C-0194, Reference 1). During testing on ATEGG XTC34 Build 2, the dual alloy impeller experienced high-cycle fatigue damage to an impeller blade in an area completely unassociated with a bond joint.

ATEGG XTC34 Build 2 testing requirements were completed with the Ti 6-2-4-6 impeller initially used on ATEGG XTC34 Build 1. At the completion of the testing, it was discovered that this component also had experienced a high-cycle fatigue (HCF) failure, this time in the backface/blade interface area. This disk was then cut up and the specimens excised as shown in Figure 2. The circular section of Figure 2 presents an impeller view from the forward looking aft direction as located in the engine. Section AA and BB shows the axial location of the HCF test specimens within the impeller cross section. As shown is section AA, S3 and S4 are subsize sheet specimens taken from mid radius and R3 and R4 are subsize sheet specimens taken from the rim of the impeller. F2 and F6, and all three specimens shown in section BB are full size round HCF specimens. This pattern of test specimen removal was repeated throughout the eight impeller sections as shown in the radial view. Figure 3 describes

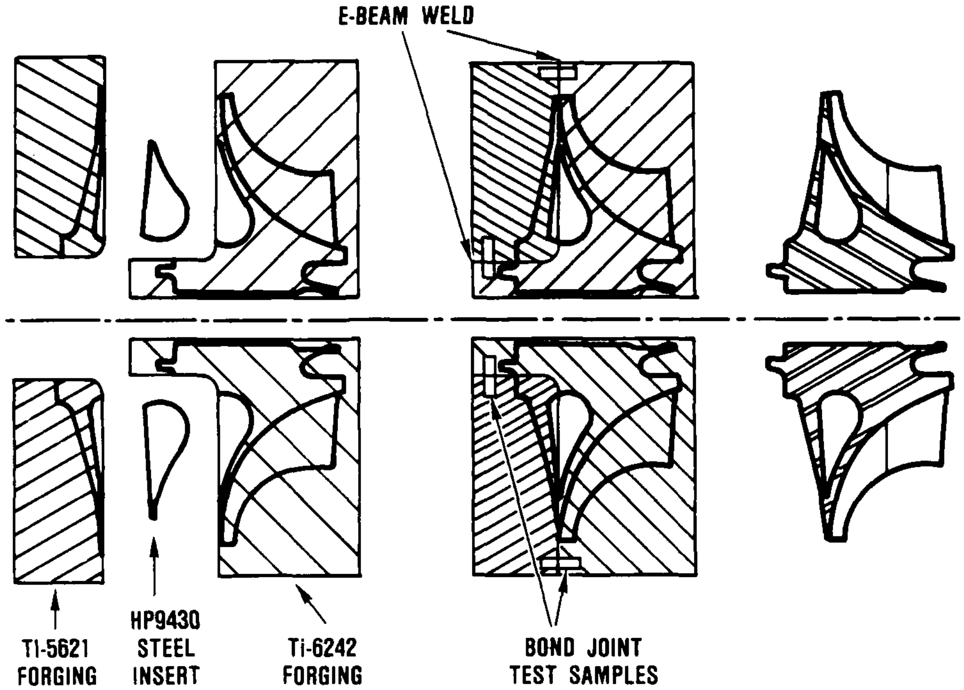


Figure 1. Dual-Alloy Impeller Fabrication Process. Developed Under the ATEGG 1131-2 Program.

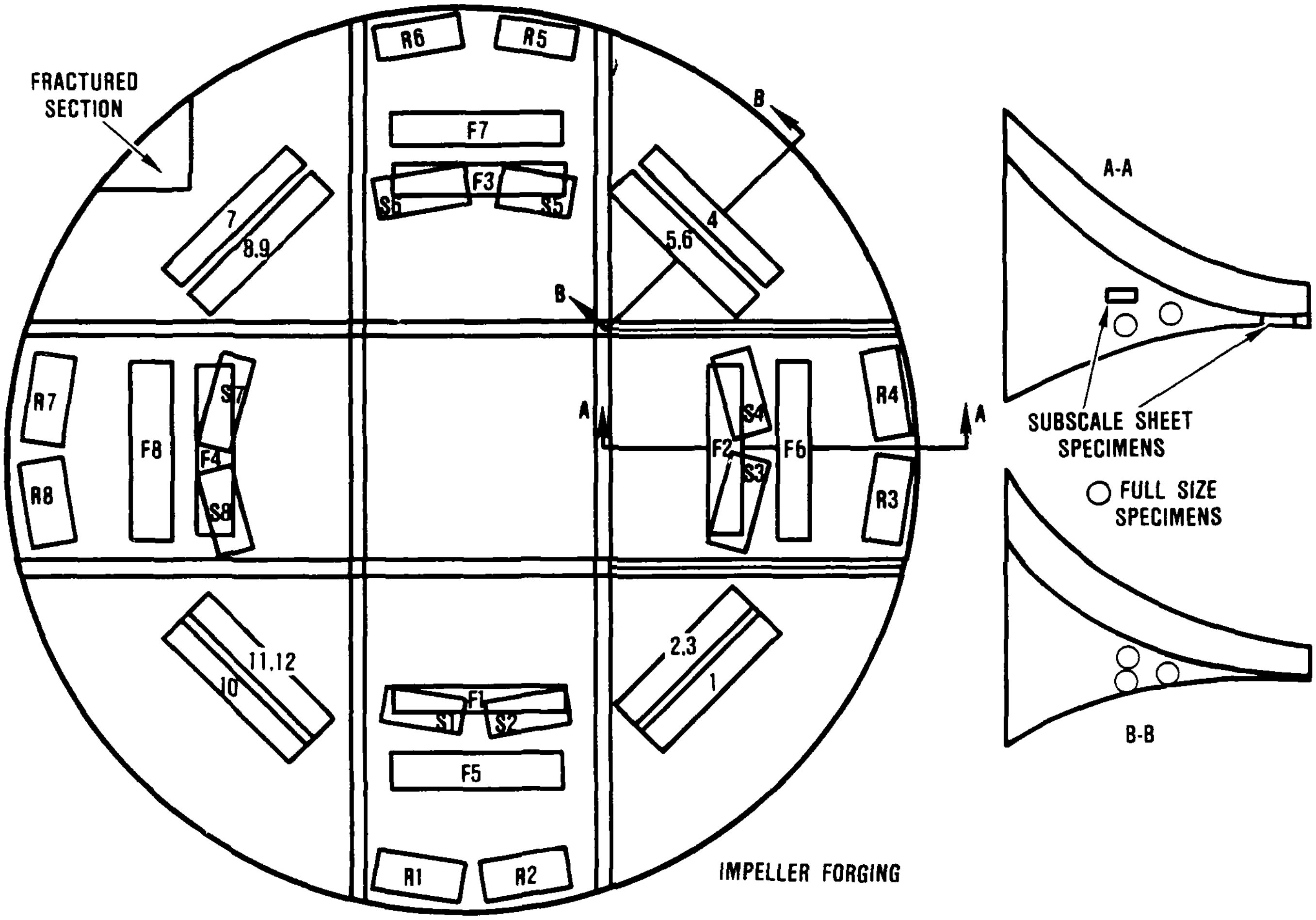
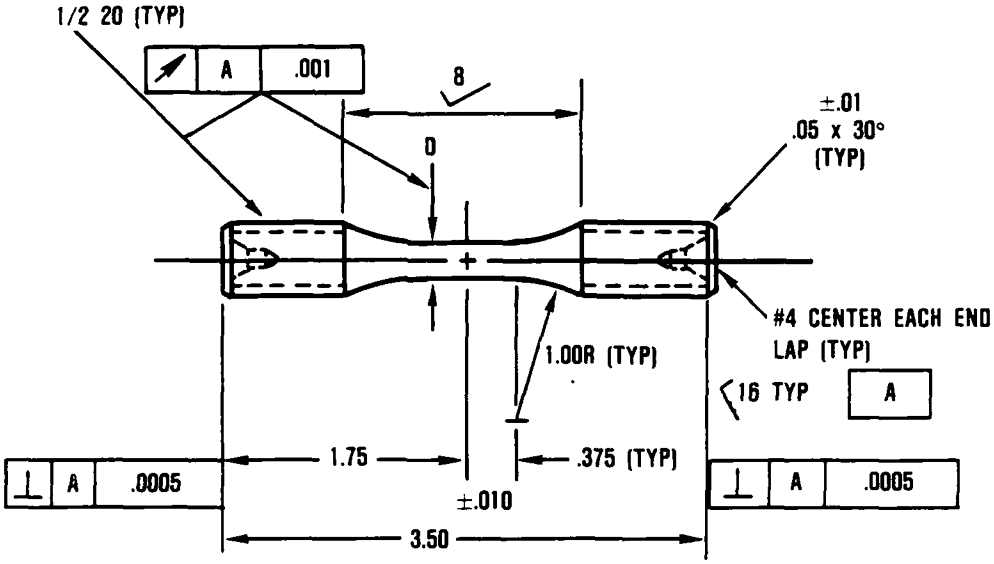


Figure 2. Cross-Section Test Plan for Test Slices Representing Serial No. 2 and 3, and Impeller, Serial No. 1



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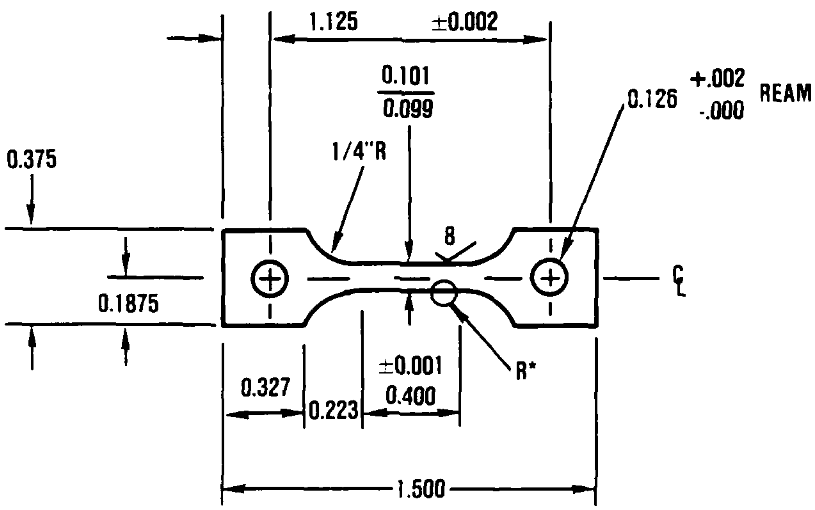
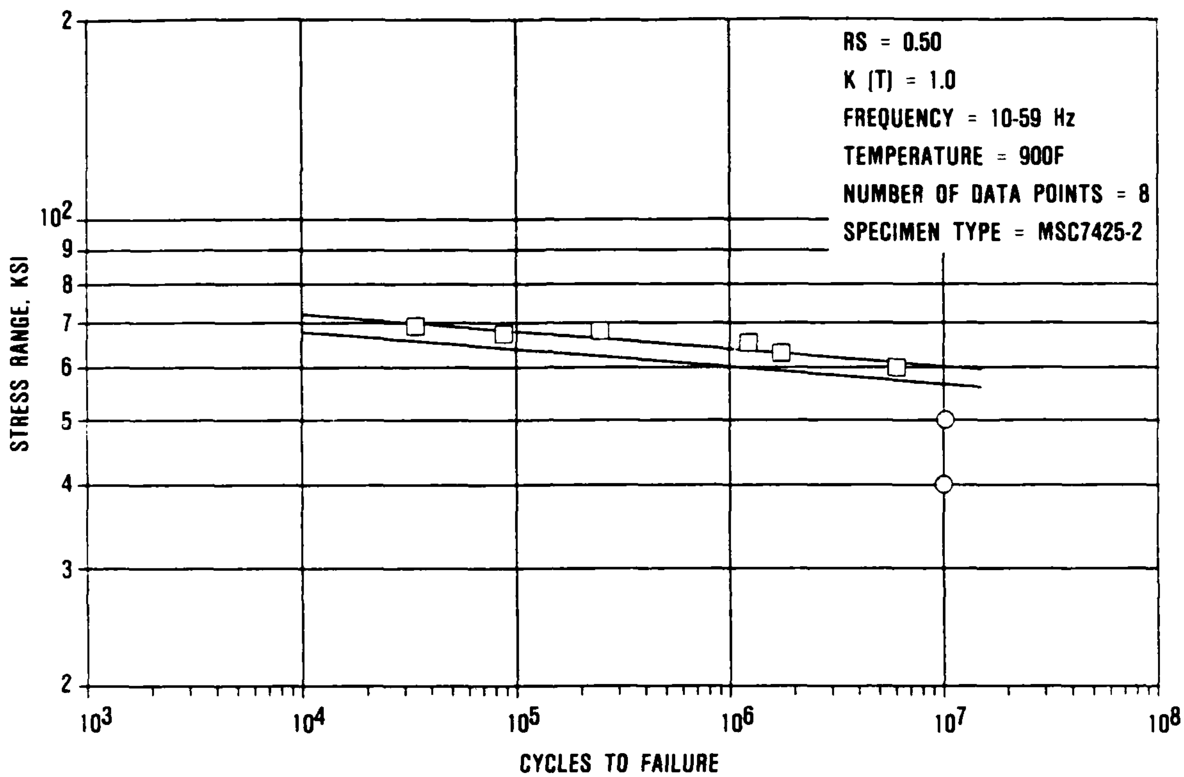


Figure 3. Test Specimen Configuration for Tension-Tension HCF.

the geometry of these test specimens with the top figure showing a fullsize fatigue bar and the bottom figure describing a subscale specimen.

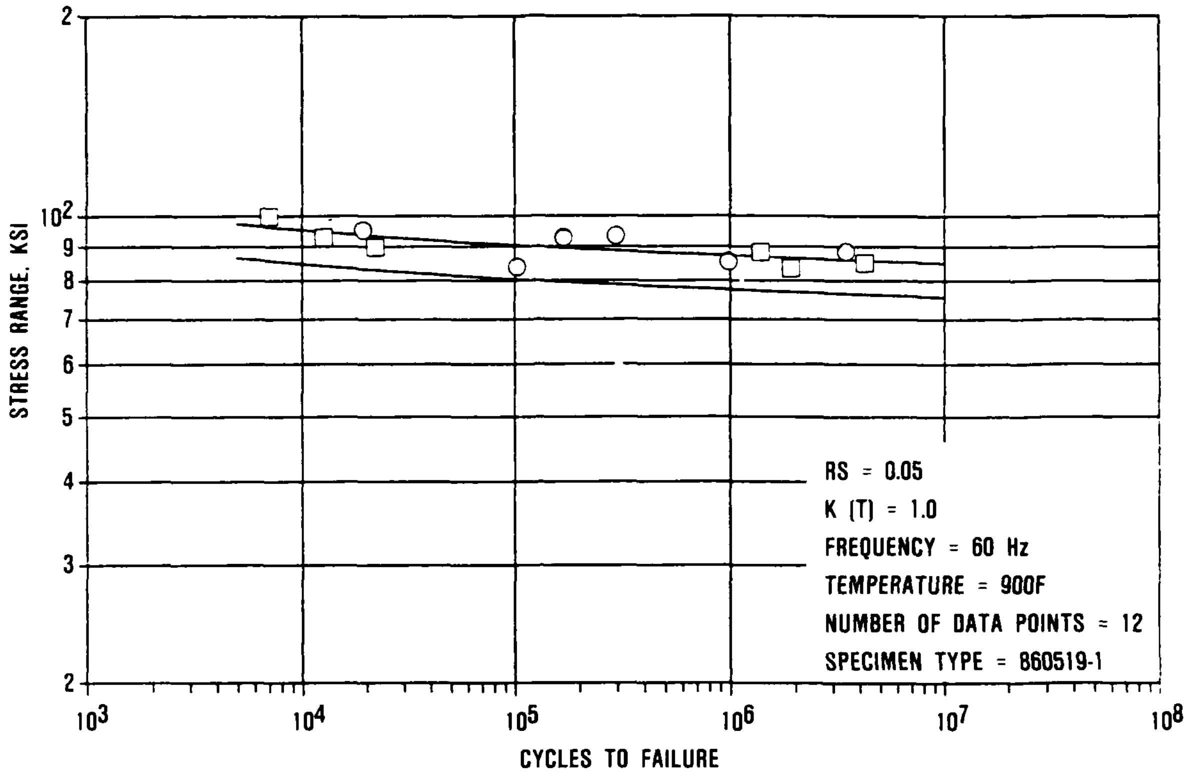
The test specimens described above were tested in High-Cycle Fatigue at 900F, in an axial-axial mode with the results shown in Figures 4, 5, and 6. Various R ratios (R = 1 $\Delta\sigma/\sigma max$) were used and are listed on each of the three curves. Initial loading conditions were chosen in an attempt to obtain lives within 10^5 to 10^7 cycles. Subsequent stress loading conditions were determined to increase or decrease lives, dependent upon the initial results. In general, the HCF results obtained from this test program were about as expected of the Ti6246 material, taking into account the processing history of the component, and would not have been expected to be a cause of failure in the part. The impeller was therefore redesigned using GED funds to diminish the stresses in the component, and thereby assure a safe JTDE XTE34 test.

With the limited quantity of impellers required for this program, closed die forging tools were not procured. The impellers were machined from open die, press-forged pancakes. Therefore, large diameter billet stock was required to produce the oversize pancakes. In addition, billet material in inventory and scheduled for futher reduction was used to meet the schedule requirements. The combination of large diameter billet and insufficient reduction produced a macrostructure much coarser than would be permissible on a production Ti 6-2-4-6 rotating component. For this reason, the failed impeller (Serial No. 1) was sectioned, as described above, for tensile and HCF evaluations under the ATEGG program to verify that forgings of this size and configuration met the desired mechanical property range for the redesigned Ti 6-2-4-6 impeller. The forgings were then used for the GED-funded redesigned JTDE impeller.



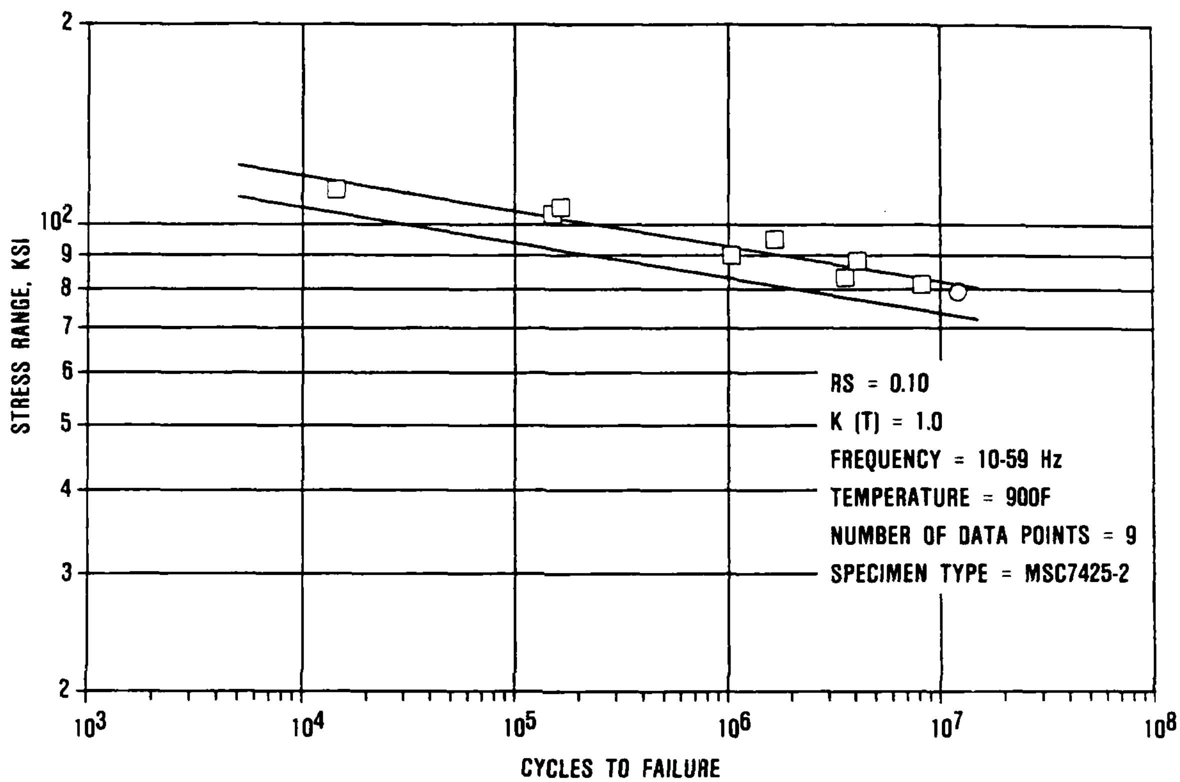
HCF MODEL OF TEST DATA TEMPERATURE = 900F K (T) = 1.0 R (STRESS) = 0.5	□ = IMP MID-RADIUS DATA IS SOLUTION TREATED AND AGED ○ = RUNOUT	DATA SOURCE TEST DATA: DRF1853

Figure 4. Full Scale Specimens from Impeller Mid-Radius with High Stress Ratio.



HCF MODEL OF TEST DATA TEMPERATURE = 900F K (T) = 1.0 R (STRESS) = 0.05	□ = RIM ○ = IMP MID-RADIUS DATA IS SOLUTION TREATED AND AGED. SHEET DATA	DATA SOURCE TEST DATA: DRF1853

Figure 5. Subscale Sheet Specimen HCF Response from Impeller (S/N 1).



HCF MODEL OF TEST DATA TEMPERATURE = 900F K (T) = 1.0 R (STRESS) = 0.1	□ = IMP MID-RADIUS DATA IS SOLUTION TREATED AND AGED ○ = RUNOUT	DATA SOURCE TEST DATA: DRF1853

Figure 6. Full Scale Specimens from Impeller (S/N 1) Mid-Radius Location.

2.2 HP Turbine Blades

The HP blades used for the JTDE XTE34 engine test, which were borrowed from the XTC34 program, were of CMSX-3 single-crystal (SC) cast material. Single-Crystal nickel based superalloys were selected for the XTE34 turbine blades because of their mechanical property advantages over any alternative material. Very large fatigue life improvements are found in directionally cast (DS or SC) components due to their relatively low modulus in the (001) direction versus equiaxed material. The differences in moduli can account for a reduction of strain induced loads of approximately 40 percent, which can account for orders of magnitude improvement in component lives. The elimination of grain boundaries in single crystals has allowed the development of nickel base superalloys devoid of the low-melting point grain boundary strengthening constituents, which allows higher-solution temperatures prior to the onset of incipient melting. The more complete solution treatments allows a more controlled microstructure with an associated increase in mechanial properties over both equiaxed and DS materials. Figure 7, 8, and 9 show the extent of the improvement of mechanical properties of the single-crystal alloy CMSX-3 over typical conventional and directionally solidified nickel base superalloys. CMSX-3 is a well characterized SC alloy similar in behavior to most of the first generation SC alloys. GED funded an extensive materials characterization program on this alloy, which was previously reported in the GED Mate 3 final report (contract No. NA53-20073, Reference 3).

2.3 HP Turbine Disk

A high-strength alloy with good temperature capabilities was selected for the HP turbine disk. AF95, an alloy developed by General Electric under MATE and other government program funding, was found to have the necessary properties.

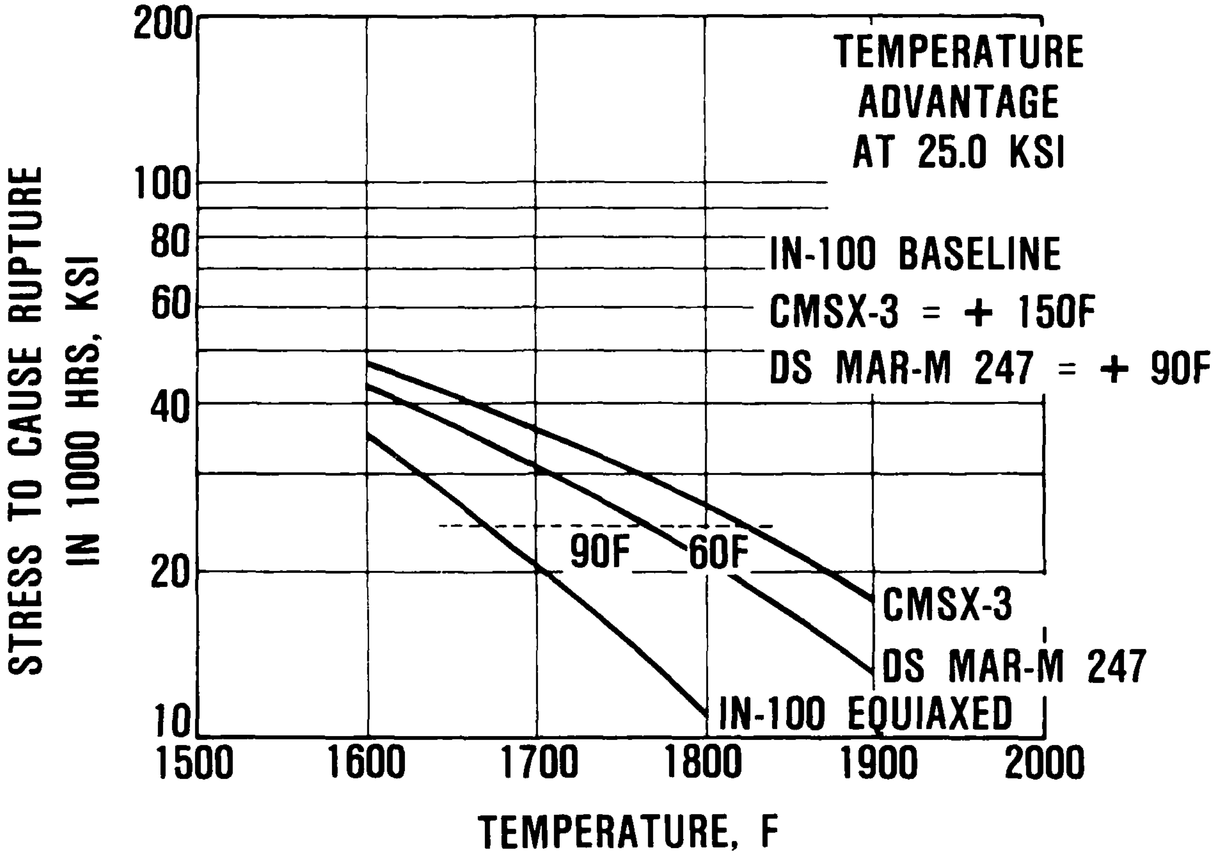


Figure 7. Comparative 1000-Hr Stress Rupture Properties.

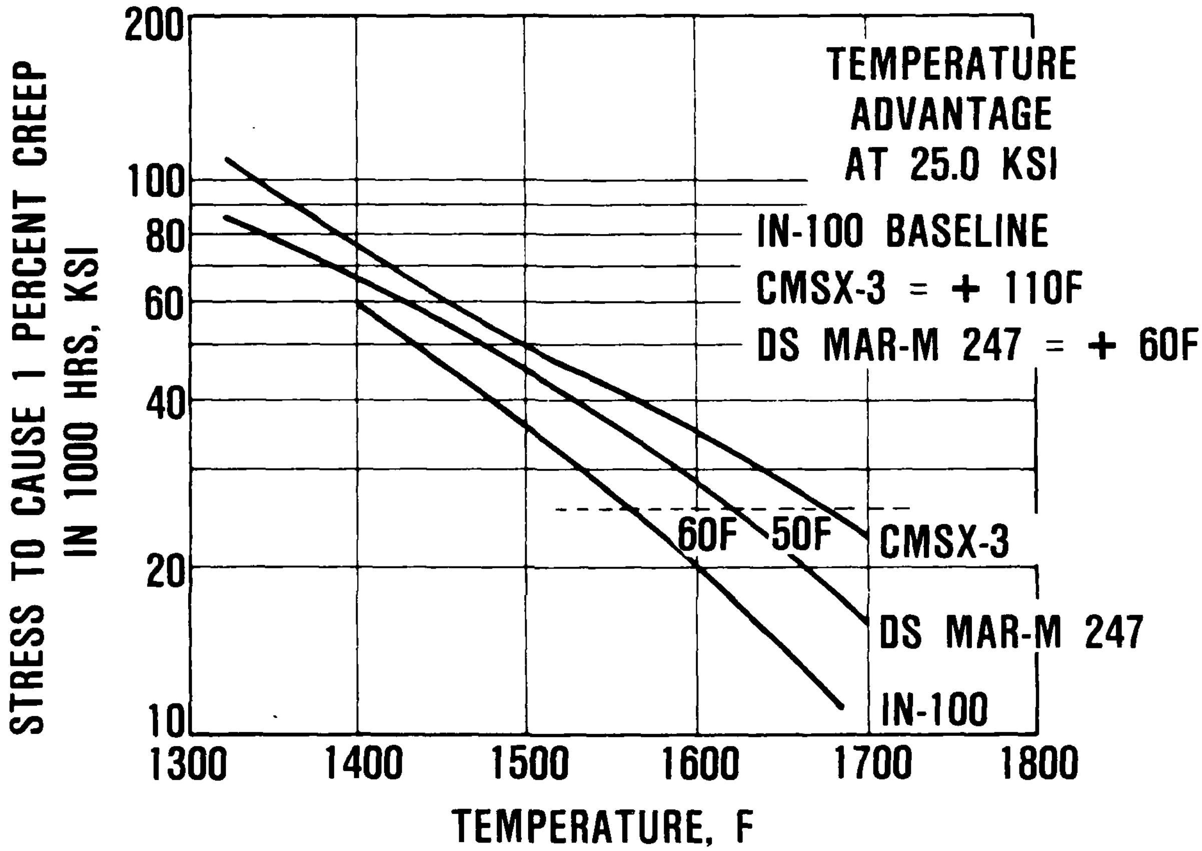


Figure 8. Comparative 1-Percent Creep Properties at 1000 Hours.

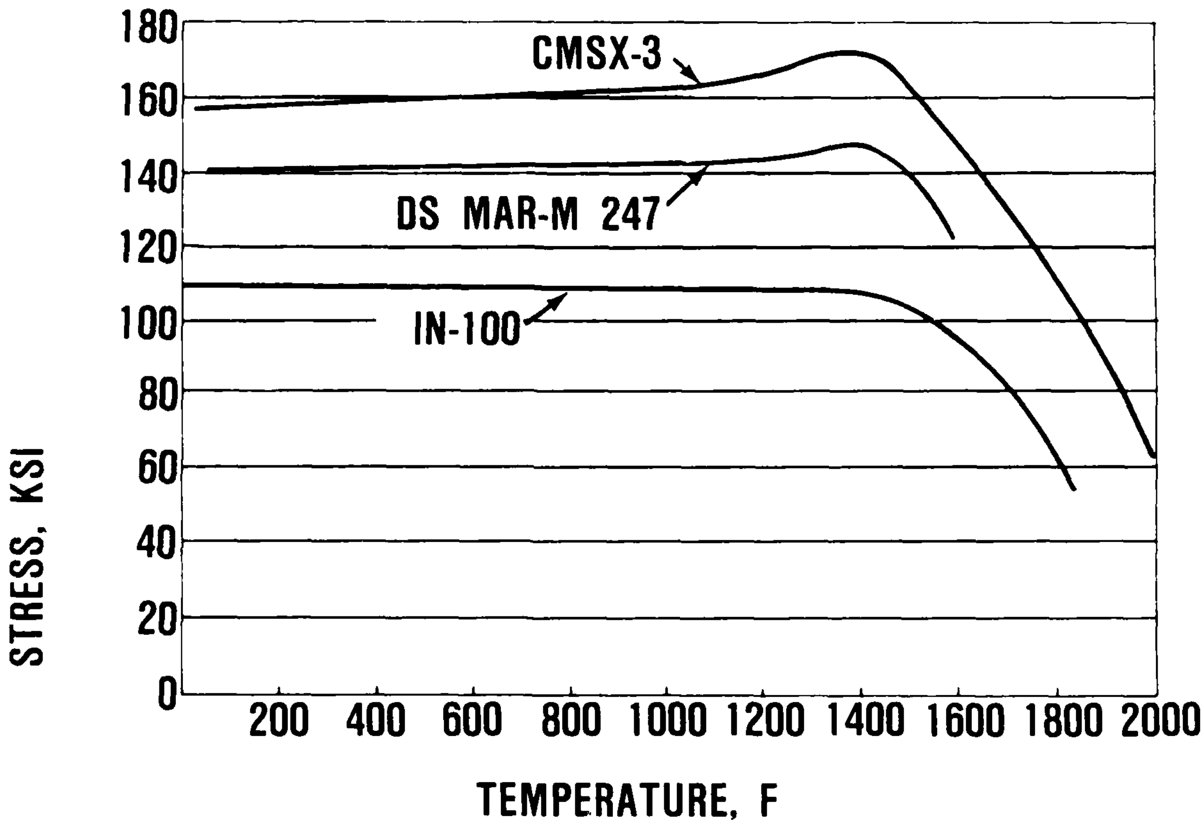


Figure 9. Comparative Ultimate Tensile Strengths.

A modified heat treat, consisting of an air-cool rather than an oil quench from the solution, was developed to minimize the schedule problems that would be encountered in low-volume applications such as demonstrator engines. The material with the modified heat treatment has been characterized by GED and found to have adequate strength for this application.

This material performed flawlessly during ATEGG testing with over 100 hours of run time. This material was subsequently used in JTDE engine testing to provide low risk.

3.0 LOW-PRESSURE (LP) COMPONENTS

3.1 LP Turbine Blades

The material used for the Navy LP turbine blades in the JTDE was SC Mar-M 247. Under the Navy Program, this blade was initially designed to take advantage of the superior creep and rupture capabilities available in the first generation SC alloys, NASAIR 100 or CMSX-3. These alloys obtain their beneficial mechanical properties primarily from improved heat treat response due to the higher solution temperature capabilities of the alloys, as described earlier and in the MATE 3 final report (Reference 3). This was done by removing the grain boundary strengthening constituents from conventional alloys. These elements (especially carbon, zirconium, and boron) were all melting point depressants which created a limitation to the degree of solutioning an alloy could withstand before localized melting, within the alloy microstucture, would occur.

The removal of these low-melting point constituents from superalloys was made practical by the single-crystal casting process with its resulting elimination of grain boundaries. The ability to raise the solution temperature to approximately 2375F results in an essentially fully solutioned structure. This occurs when the gamma prime, the hardening mechanism member in Nickel based superalloys, can be uniformly precipitated by additional heat treatments throughout the component microstructure, thus accounting for the optimum mechanical properties. The higher solution temperatures, however, greatly increase the tendency of alloys to have surface recrystallization; a condition considered potentially catastrophic in single-crystal alloys.

The configuration of this blade (Figure 10) consists of a low-aspect ratio, highly twisted airfoil with a relatively large tip

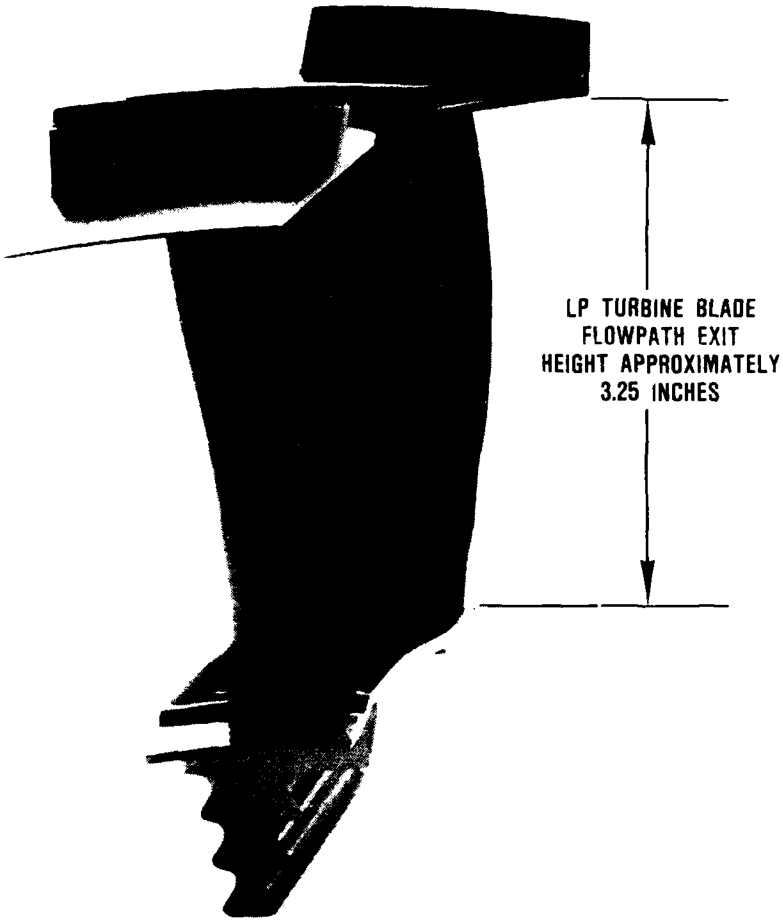


Figure 10. The Low-Pressure Turbine Blade has a Low-Aspect Ratio, Highly Twisted, and a Relatively Large Shroud.

shroud. This configuration proved to be beyond the SC casting capabilities available at the time and resulted in a highly constrained component that was very susceptible to recrystallization during solution heat treat. All attempts to solution heat treat the JTDE LP turbine blades in NASAIR 100 or CMSX-3, resulted in the formation of recrystallized grains on the surface of the blades.

As a final attempt to obtain SC castings for both rig and engine tests, the casting vendor suggested the use of MAR-M 247 as the SC alloy. The alloy was used and successfully cast into blades, and solution treated without recrystallization. These blades were machined and warm rig tested in the Navy program and subsequently used in the JTDE XTE34 engine test. Further description of the material effort for the LP turbine is discussed in the Navy LP turbine program final report (report No. 21-5115; contract No. N00140-80-C-0581, Reference 2).

Prior to the XTE34 test, an analysis of the mechanical property data for SC MAR-M 247 indicated it would have adequate rupture capabilities for the temperatures expected in the XTE34 application.

During testing of the XTE34 (details reported in JTDE I XTE34 Test Report, Reference 4), some LP blades experienced creep rupture failure in the tip shroud region. This was the result of operating temperatures in excess of the design level.

In Figure 11 the microstructure of the single-crystal MAR-M247 blades is shown in the area adjacent to the fracture face from the tip shroud rupture failure. The metallographic structures shown in these photos is indicative of acceptably processed MAR-M247 material. As shown in these photos, an appreciable amount of non-solutioned coarse gamma prime still exists in the microstructure along with the expected amount of carbides. Although these features would not be expected in conventional single-crystal alloys which

Figure 11. Posttest Examination Shows Representative Microstructure and Fractures of the LP Turbine Blades.

had undergone very high-solution heat treatments, they would be expected in MAR-M247 material which is limited by incipient melting to solution treatments of approximately 2250F. This incomplete solutioning results in lower-stress rupture capabilities that can be obtained in single-crystal alloys. This decrease in properties resulted in a decrease in the margin which allowed the creep rupture failures to occur as the result of operating temperatures in excess of the design level. These temperatures were not enough to cause any obvious microstructural degradation which would be shown in Figure 11, but were sufficient to diminish the life of the components to a point in which rupture failures occurred during the engine test.

3.2 LP Turbine Vanes

The LP turbine vane on the JTDE used a "rainbow" build configuration with both monolithic CMSX-3, SC-cast vane and band segments (Figure 12), and brazed assemblies of MA-754 bands and vanes (Figure 13). CMSX-3 material is discussed in paragraph 2.2; these parts were funded by the Air Force. The MA-754 vanes were procured with GED cost share funds.

MA-754 is an oxide-dispersion strengthened nickel-chromium alloy produced by mechanical alloying. The alloys strength in conjunction with its high melting point and microstructural stability, makes it an attractive material for the extreme service conditions encountered in turbine engines.

Since welded joints would not be expected to retain a significant percentage of the alloy's stress rupture strength due to dispersoid agglomeration, a brazing procedure was developed to join the airfoils to the inner and outer end bands. The use of Alloy Metals Inc.'s "DF6" (Ni-21Cr-3Fe-3, 5 Ta-2.0B - 3.5 Al-0.010Y) braze alloy, a braze cycle of 2300F for 15 minutes and a post braze cycle of

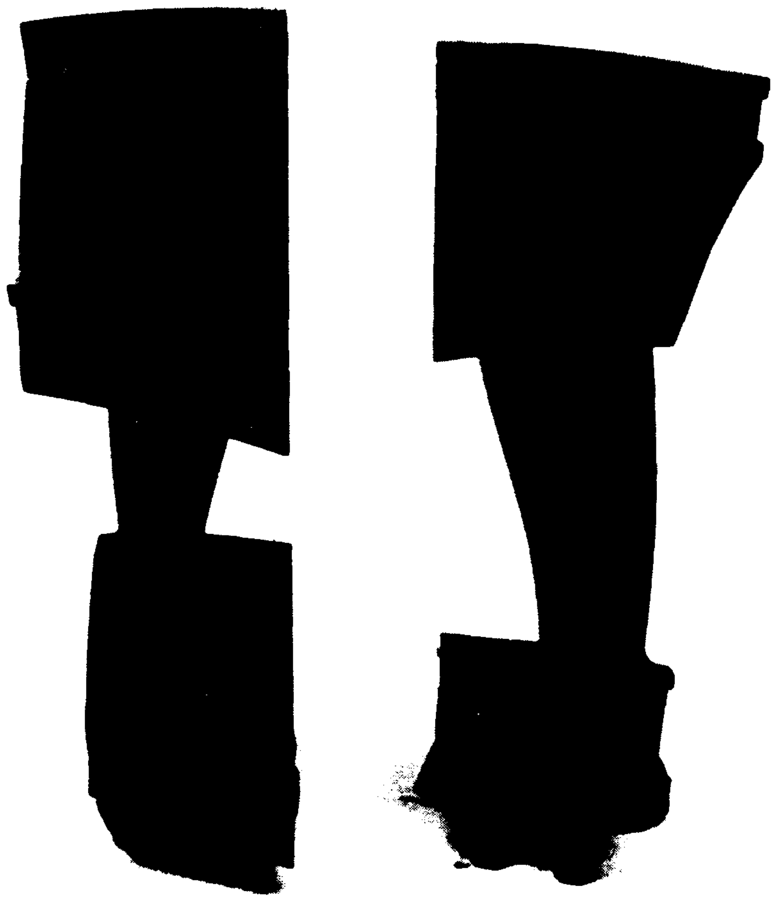


Figure 12. CMSX-3 SC-Cast Vane and Band Segments.


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Figure 13. MA 754 Brazed Vane Assemblies.

2100F for 2-4 hours produced a braze joint with adequate strength for this application.

Subsequent posttest inspection showed both the CMSX-3 and the MA-754 components to be in good condition despite operation at temperatures up to 100F higher than design intent.

4.0 SUMMARY

The XTE34 used materials previously characterized by Air Force (ATEGG) and Navy (Mixed-Flow Fan and LP Turbine) programs that provided core and low-spool components, respectively.

Additional GED-funded, materials R&D effort focused primarily on the HP compressor impeller, which had experienced a HCF failure in ATEGG testing, and on the LP turbine stator. For the latter, the hardware from the Navy program did not match the XTE34 flow requirements, and a 4 percent higher flow area variant was produced by GED. To provide incipient melting point margin (because of the high operating temperature for the uncooled LP stage), a spare set of stators using MA 754 alloy was fabricated using GED funds and tested in the XTE34.

Engine testing demonstrated that all materials behaved as intended and no material flaws or HCF initiation sites were found in any of the components examined after the XTE34 test program.

LIST OF REFERENCES

1. ATEGG Materials R&D Report, Report No. 21-5120A Date: July 1984 Contract No. F33657-82-C-0194

2. Navy LP Turbine Final Report, Report No. 21-5115 Date: February 1984, Contract No. N00140-80-C-0581

3. Low-Cost Single-Crystal Turbine Blades Volume 1, MATE Program Report No. 21-4314-1 Date: August 1983 Contract No. NA53-20073

4. JTDE I XTE34 Test Report (Classified), Report No. 21-6493 Date: August, 1987, Contract No. F33657-83-C-2004

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